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(54) **SYSTEMS AND METHODS FOR DOPPLER-ENHANCED RADAR TRACKING**

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G01S 13/58	(2006.01)
H01Q 21/06	(2006.01)
G01S 13/90	(2006.01)

(52) **U.S. Cl.**

CPC ***G01S 13/72*** (2013.01); ***G01S 13/584*** (2013.01); ***H01Q 21/06*** (2013.01); *G01S 13/9047* (2019.05)

(58) **Field of Classification Search**

CPC G01S 13/003; G01S 13/006; G01S 13/32; G01S 13/72; G01S 13/583; G01S 13/584; G01S 13/589; G01S 13/60; G01S 13/62; G01S 13/64; G01S 13/4454; G01S 13/4463; G01S 13/48; G01S 13/50; G01S 13/52; G01S 13/90; G01S 13/9005; G01S 13/9011; G01S 13/9023; G01S 13/9035; G01S 13/9058; G01S 13/9307; G01S 13/931; G01S 13/9353; G01S 13/94; G01S 2013/0236; G01S 2013/0245; G01S 2013/468; G01S 2007/356; G01S 2007/403; G01S 2007/4034; G01S 7/4026

See application file for complete search history.

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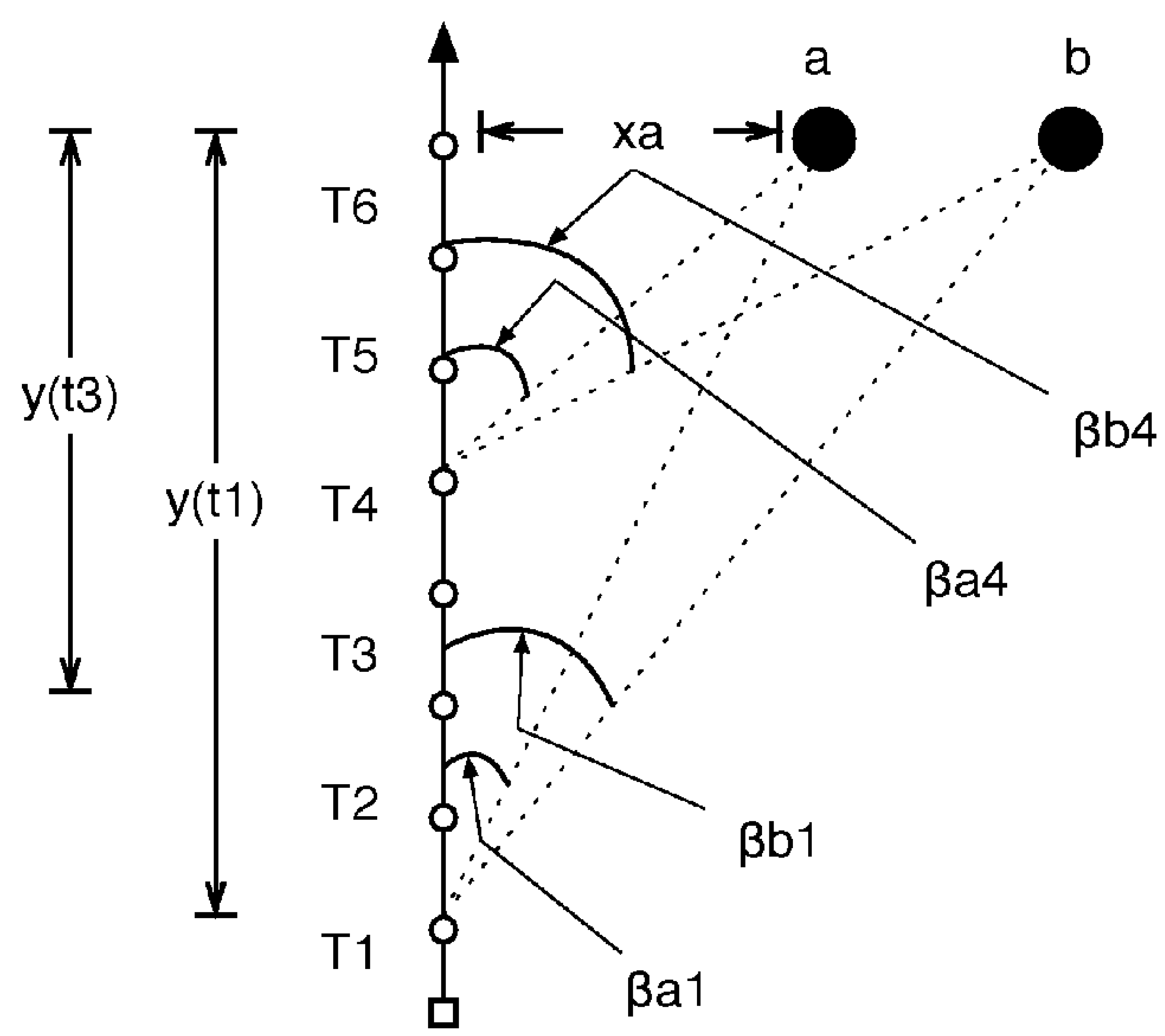
(57) **ABSTRACT**

A method for Doppler-enhanced radar tracking includes: receiving a reflected probe signal at a radar array; calculating a target range from the reflected probe signal; calculating a first target angle from the reflected probe signal; calculating a target composite angle from the reflected probe signal; and

calculating a three-dimensional position of the tracking target relative to the radar array from the target range, first target angle, and target composite angle.

22 Claims, 10 Drawing Sheets



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PRIOR ART

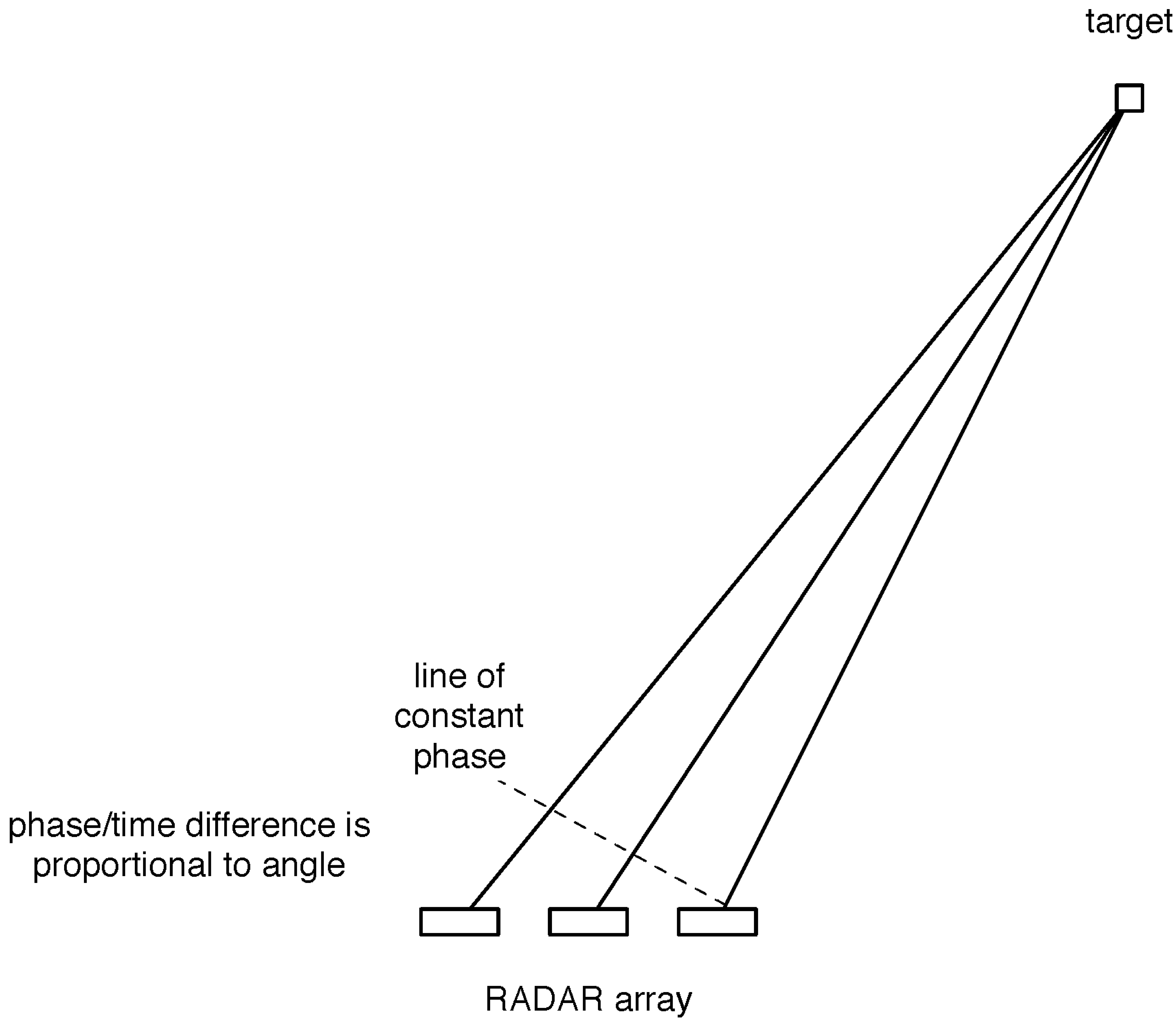


FIGURE 1

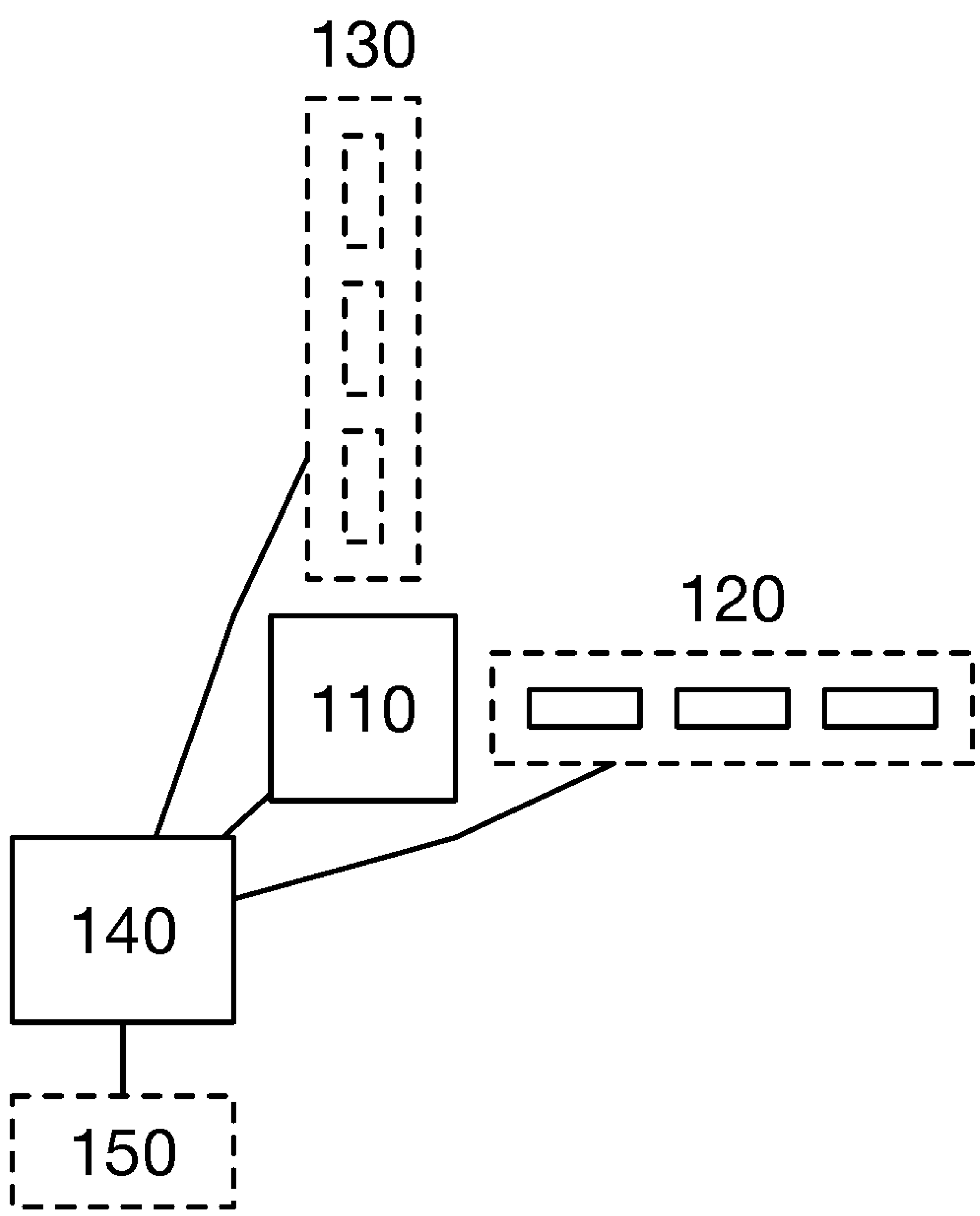


FIGURE 2

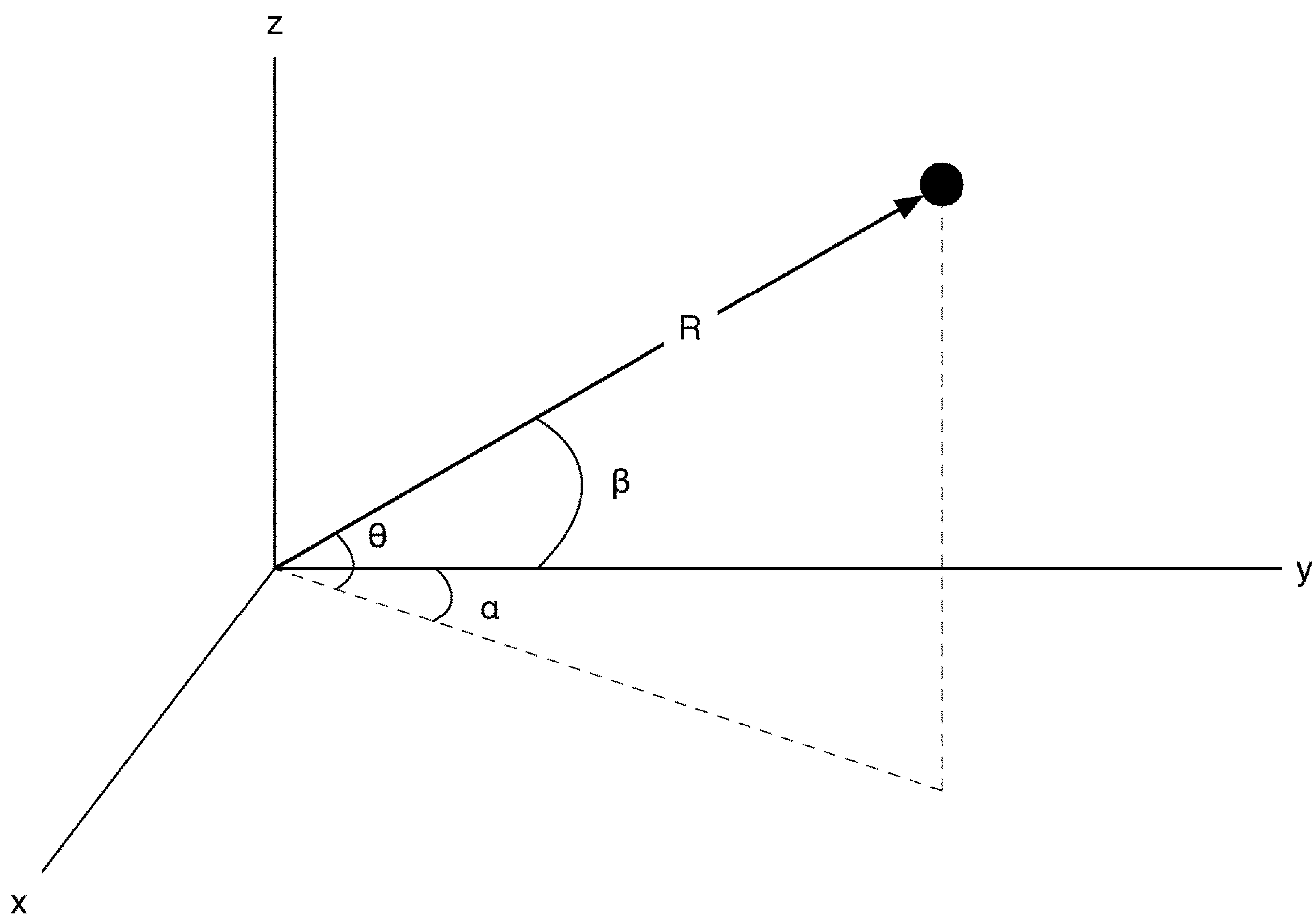


FIGURE 3A

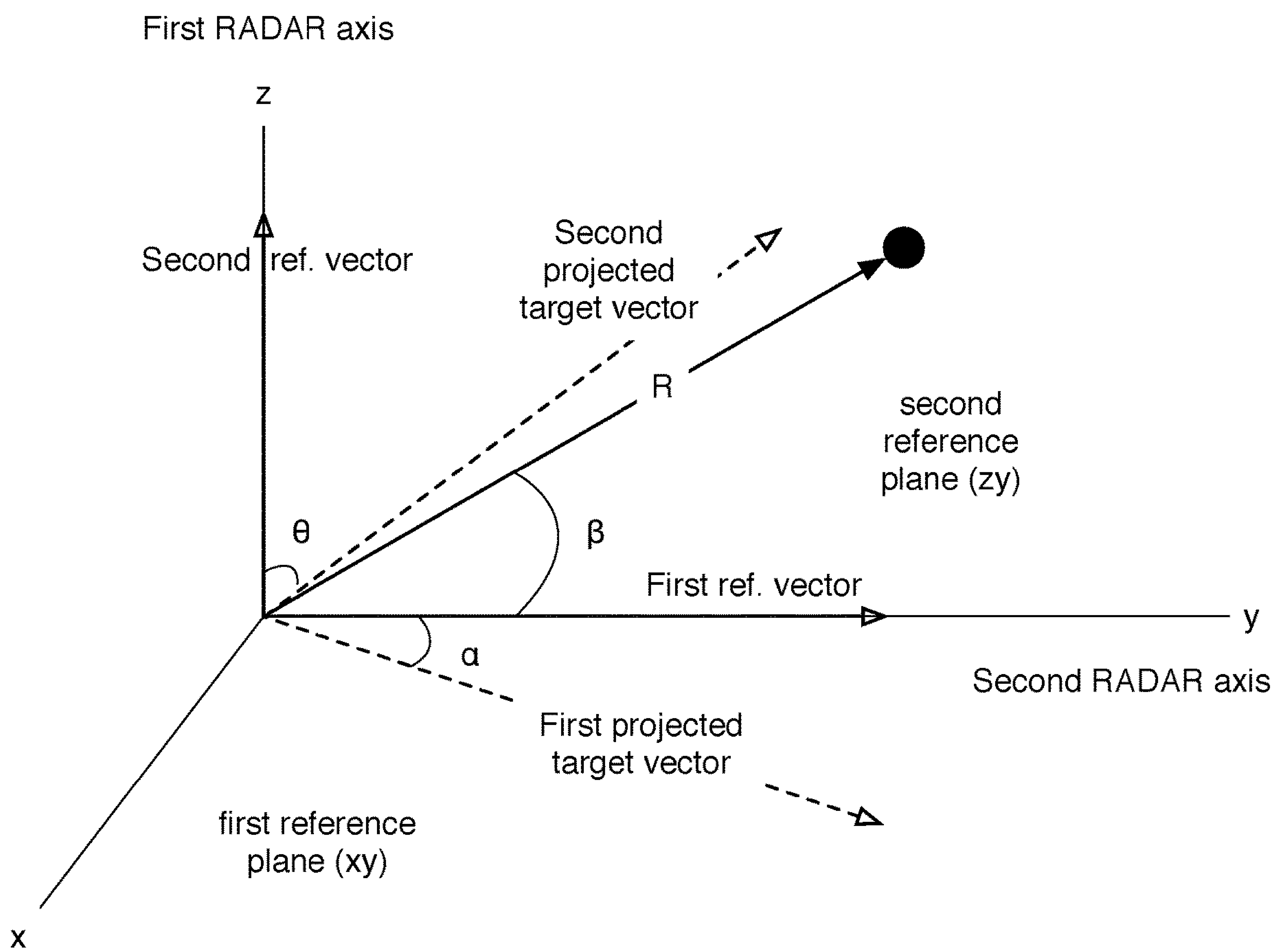

First RADAR axis
z
Second ref. vector
Second
projected
target vector
R
second
reference
plane (zy)
θ
β
First ref. vector
y
α
Second RADAR axis
First projected
target vector
first reference
plane (xy)
x

FIGURE 3B

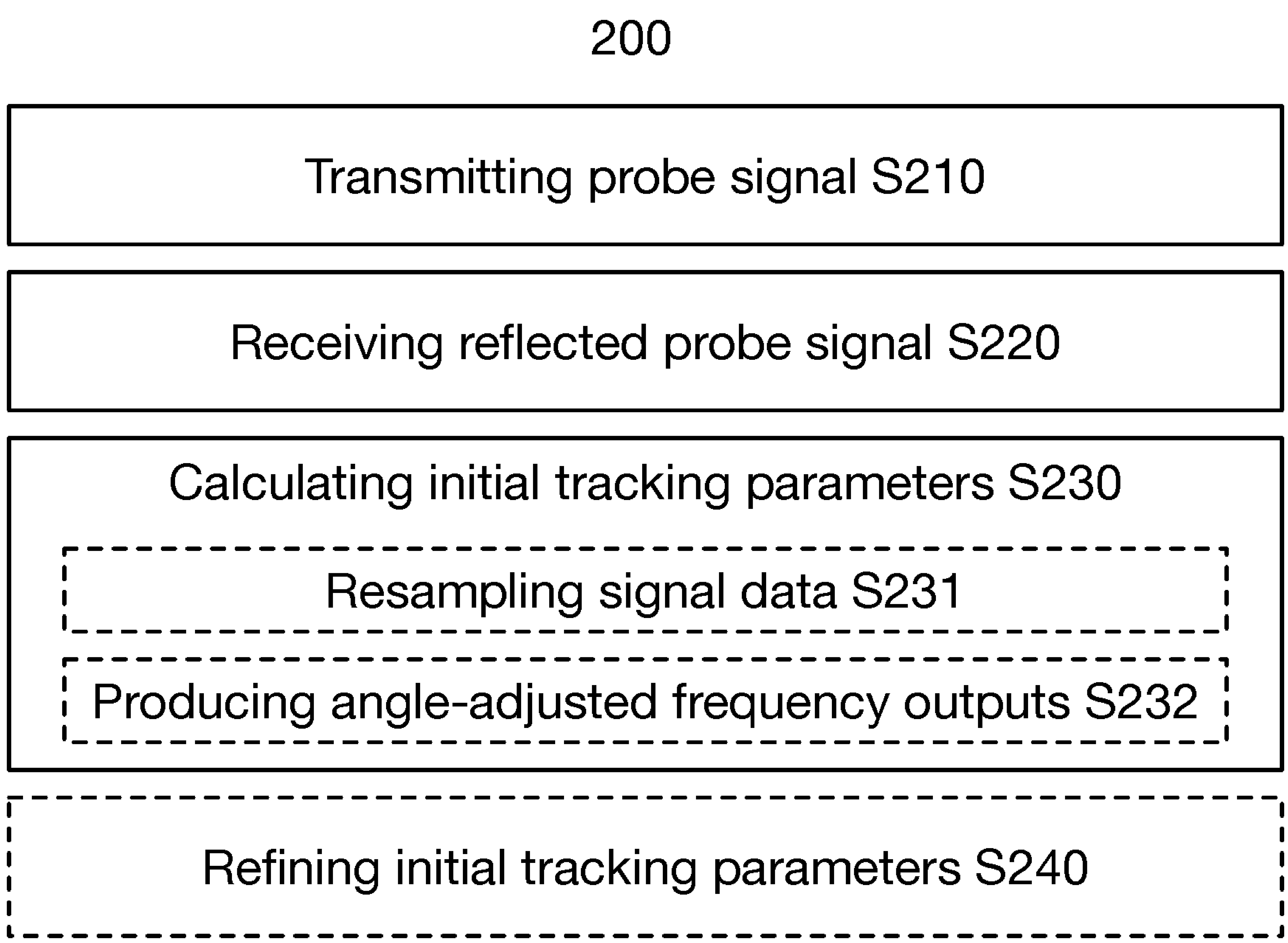

200
Transmitting probe signal S210
Receiving reflected probe signal S220
Calculating initial tracking parameters S230
Resampling signal data S231
Producing angle-adjusted frequency outputs S232
Refining initial tracking parameters S240

FIGURE 4

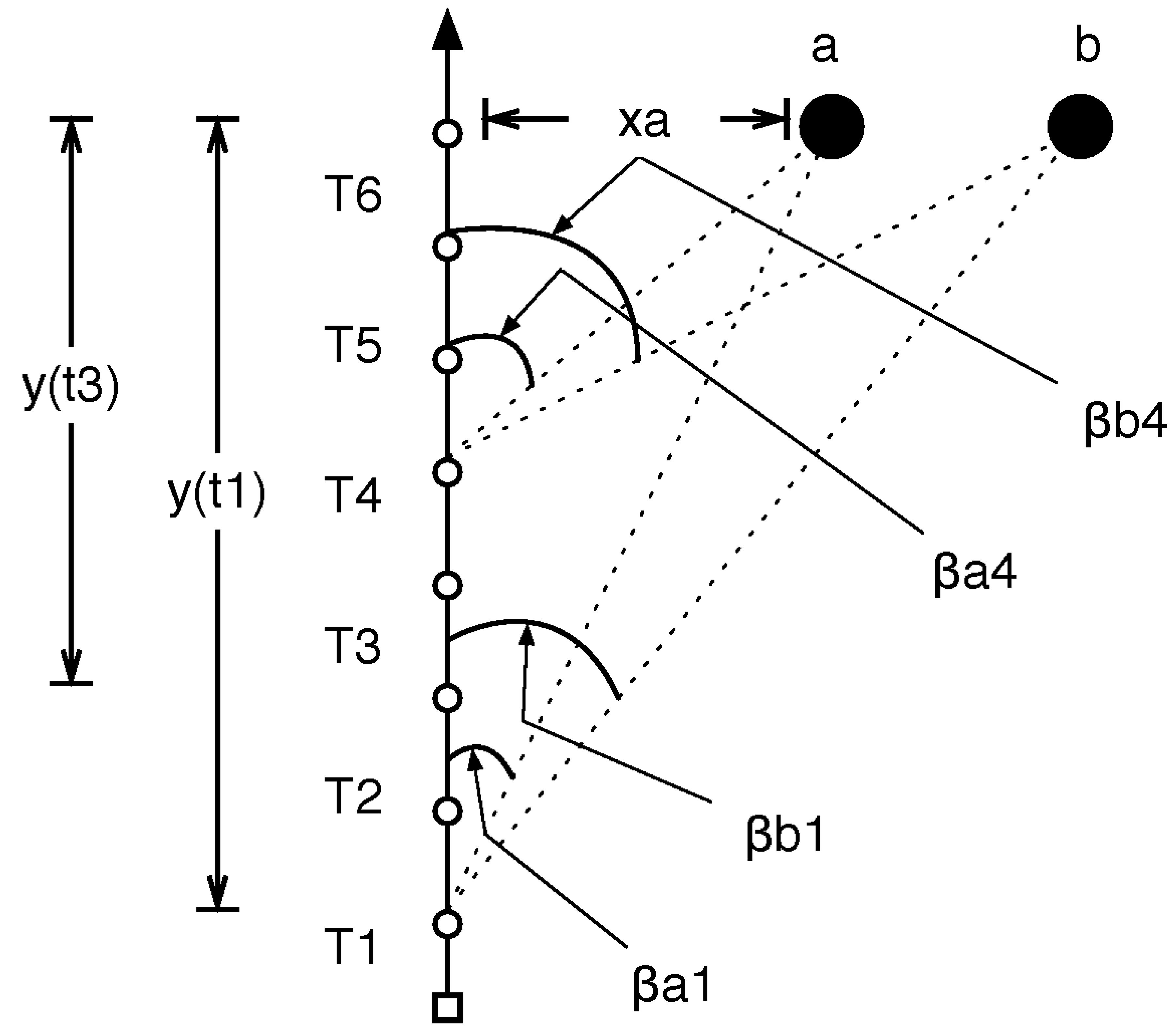


FIGURE 5A

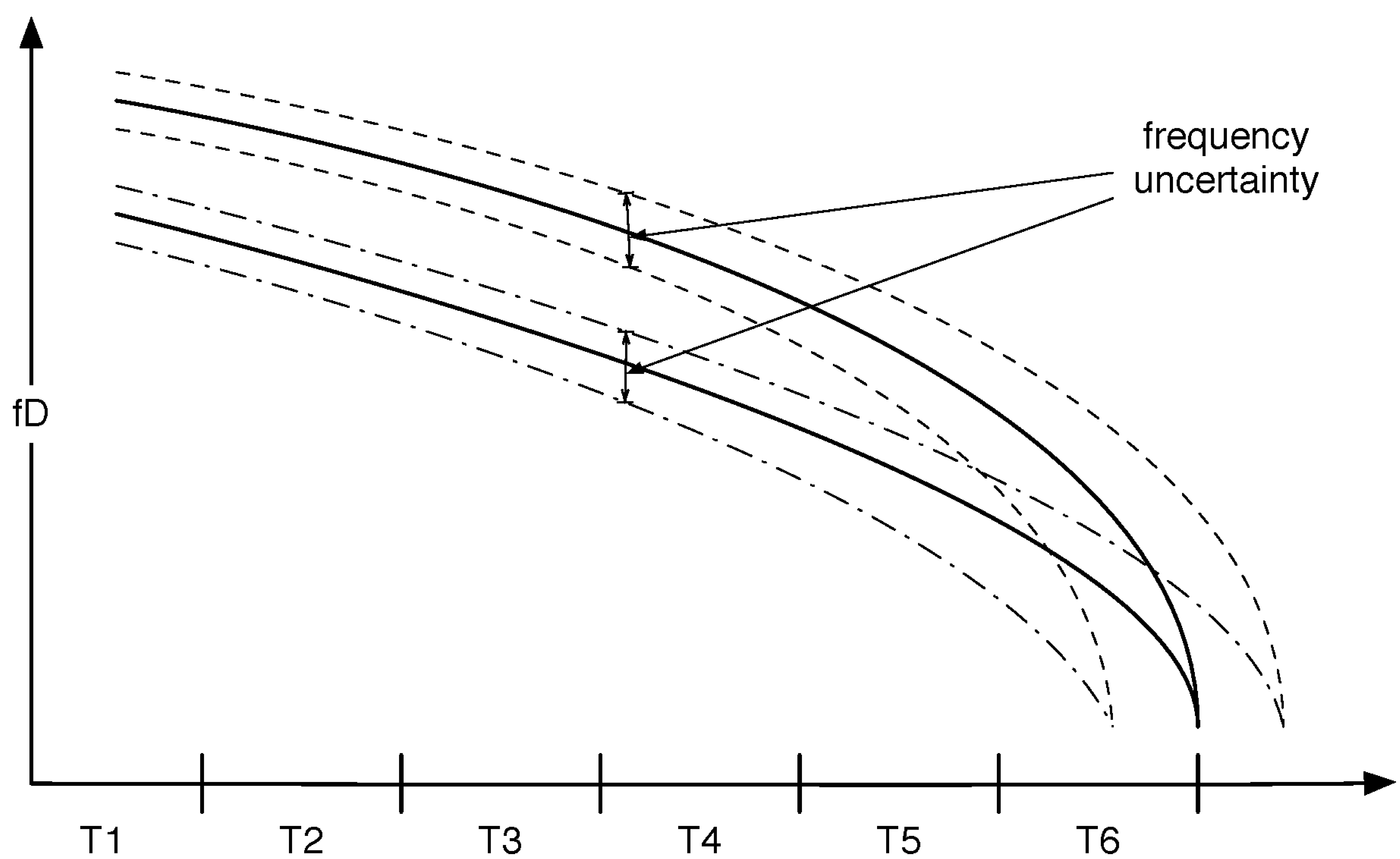


FIGURE 5B

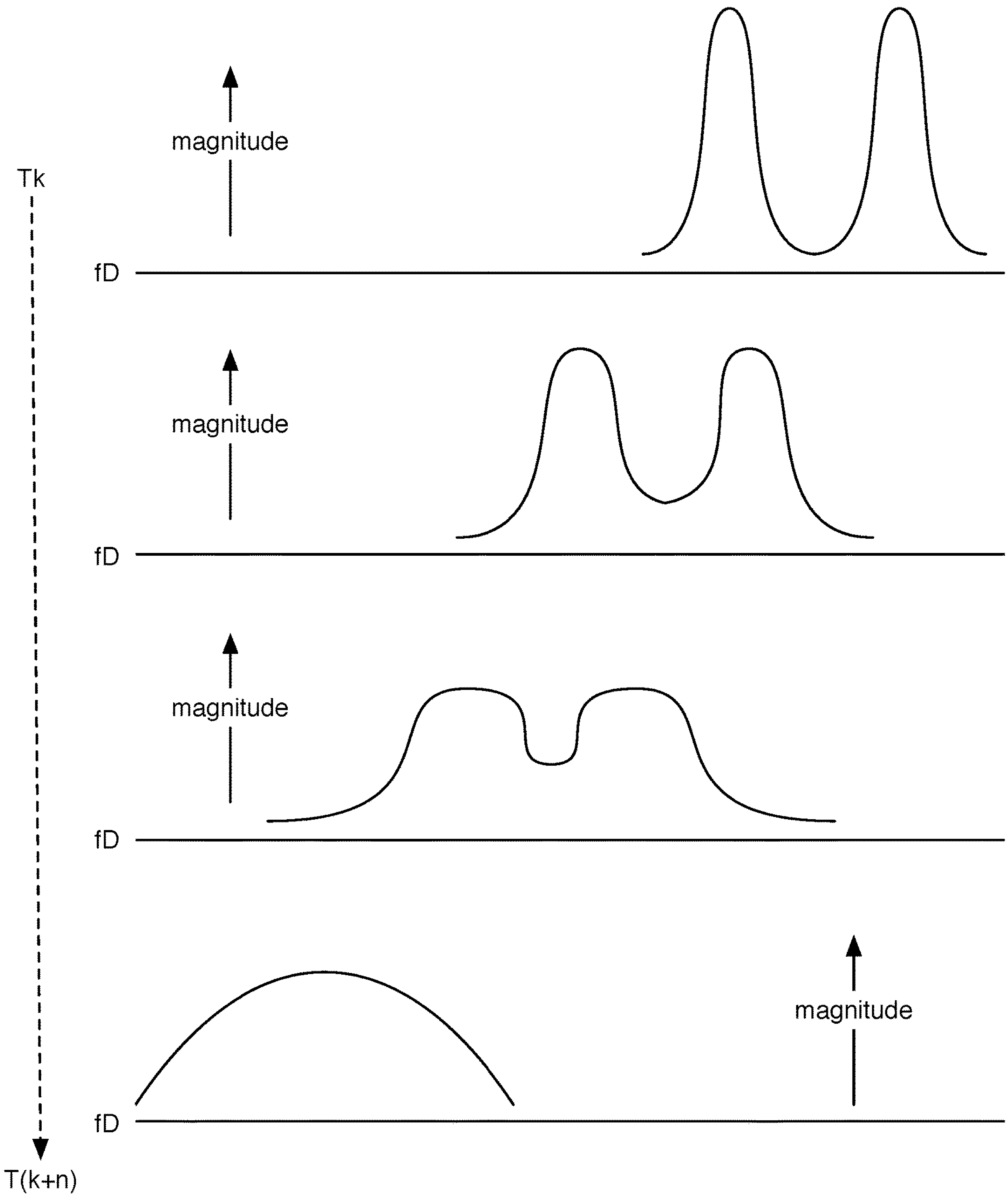
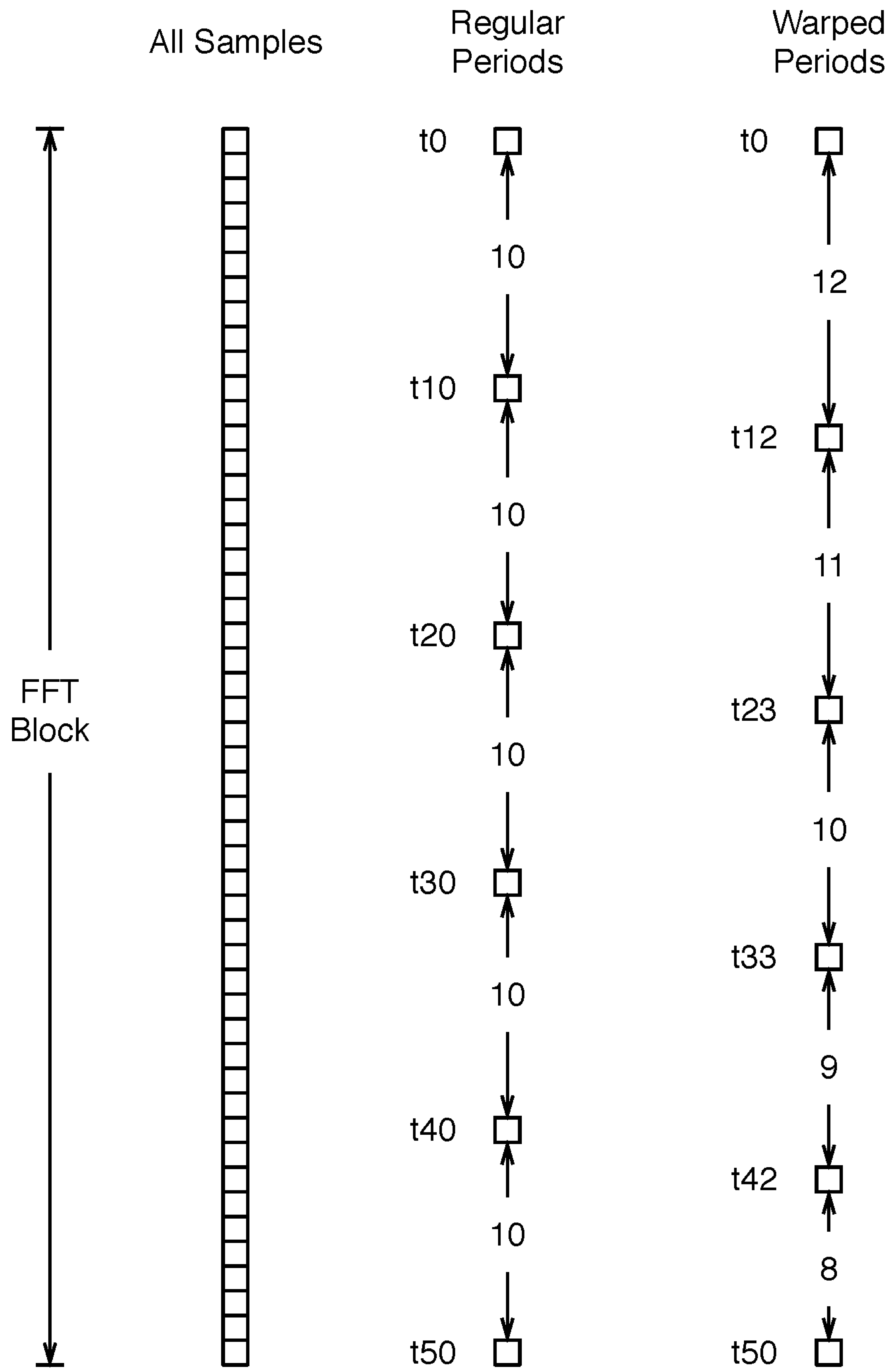


FIGURE 5C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Regular Periods
Warped Periods
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t10
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t20
10
t30
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t40
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t50
t0
12
t12
11
t23
10
t33
9
t42
8
t50

FIGURE 6

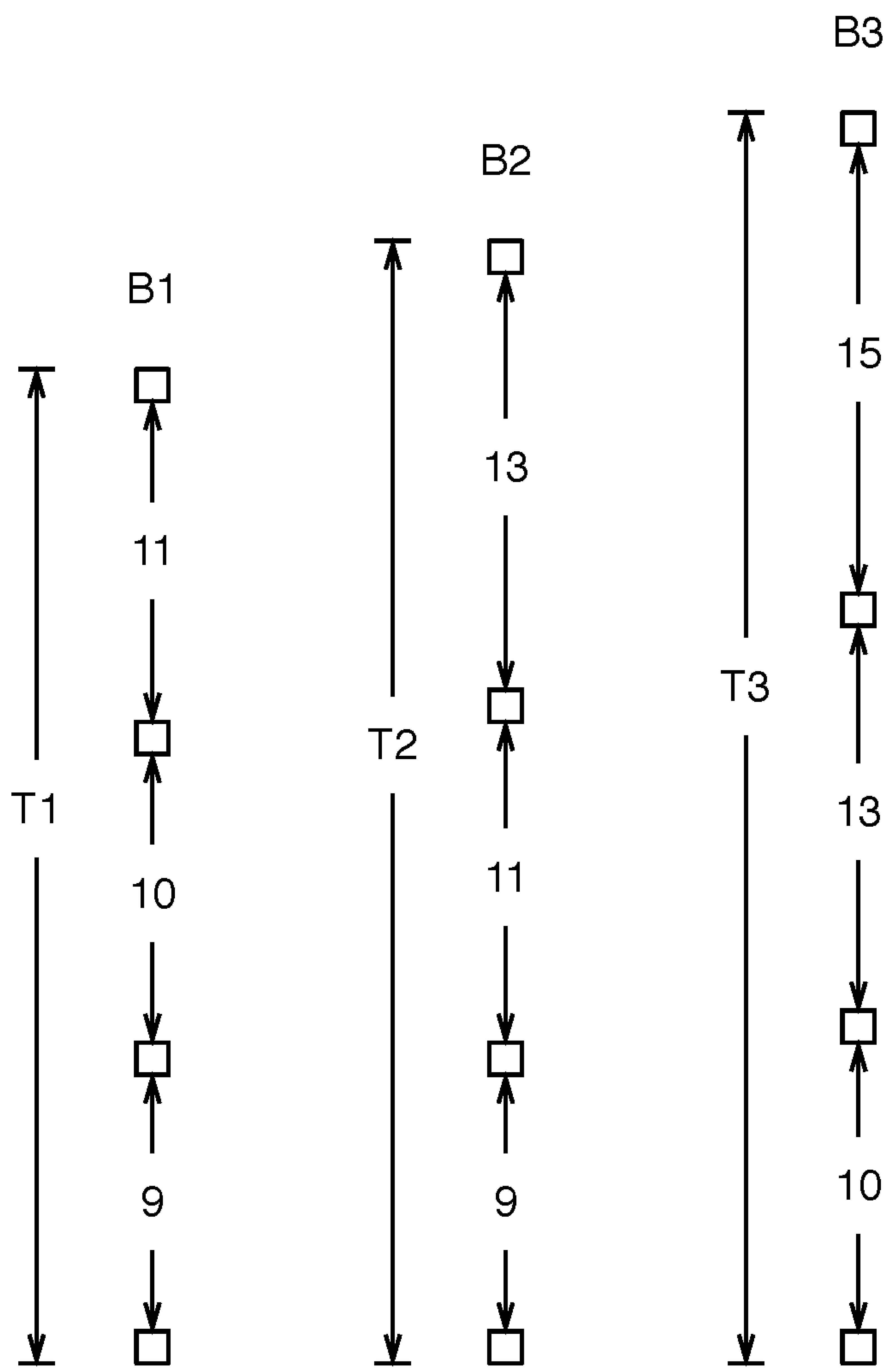

FIGURE 7

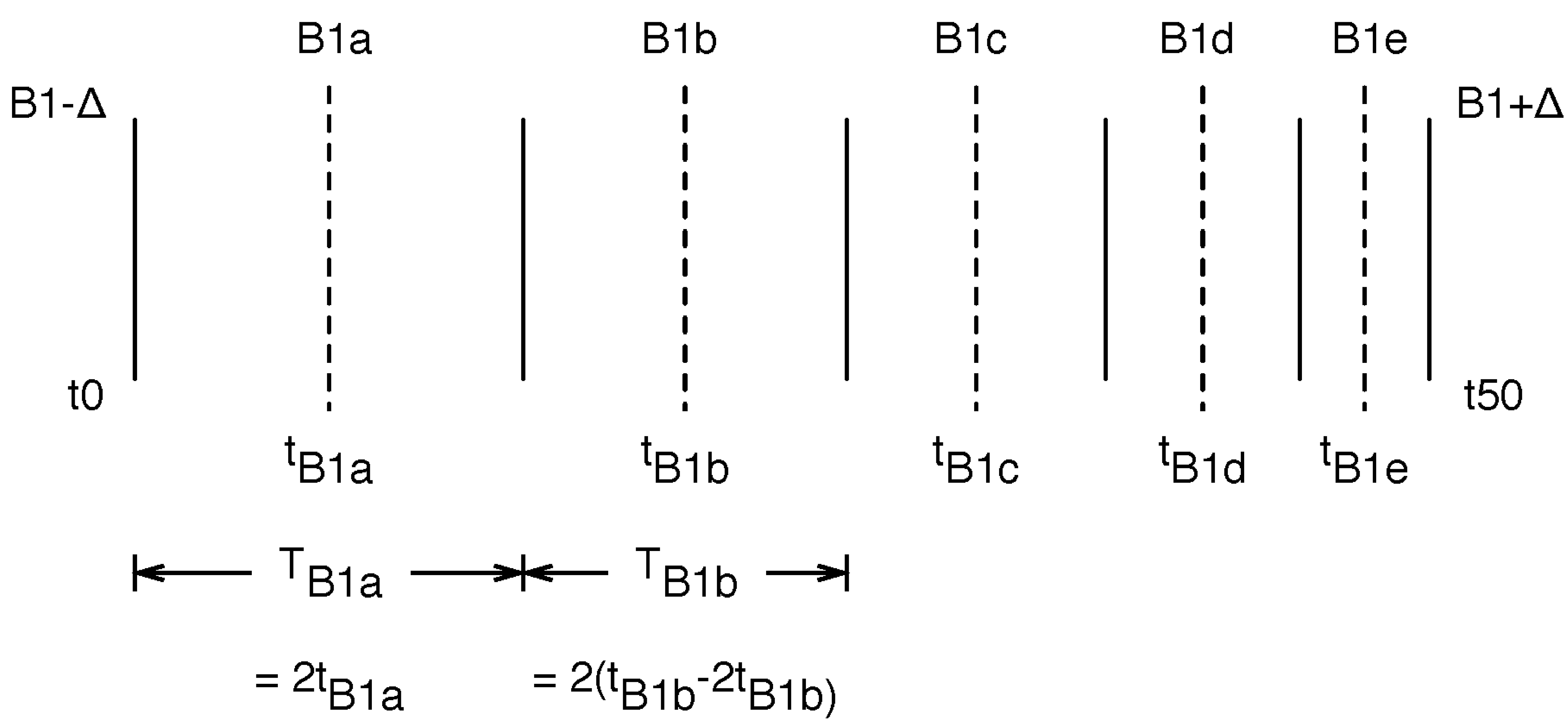
B1a
B1b
B1c
B1d
B1e
B1-Δ
B1+Δ
t0
t50
tB1a
tB1b
tB1c
tB1d
tB1e
TB1a
TB1b
= 2tB1a
= 2(tB1b-2tB1b)

FIGURE 8

SYSTEMS AND METHODS FOR DOPPLER-ENHANCED RADAR TRACKING

TECHNICAL FIELD

This invention relates generally to the radar field, and more specifically to new and useful systems and methods for Doppler-enhanced radar tracking.

BACKGROUND

Traditional array-based receivers calculate azimuth and/or elevation by measuring the time or phase difference between received probe signals at different receivers (or antennas) within the array(s), as shown in FIG. **1** (1D array), using beamforming (e.g., digital beamforming). Similar effects may be produced using a transmit array instead of a receiver array. These traditional solutions are limited: angular resolution depends both on the number of elements in the array and the angle between the array and the target:

$$\theta_{resolution} \approx \frac{\lambda}{Nd\cos\theta}$$

where N is the number of elements in the array and d is the distance separating them.

Thus, there is a need in the radar field to create new and useful systems and methods for Doppler-enhanced radar tracking. This invention provides such new and useful systems and methods.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** is a prior art example diagram of a 1D receiver array radar system;

FIG. **2** is diagram view of a system of an invention embodiment;

FIG. **3**A is an example view of a tracking target in a spherical coordinate system;

FIG. **3**B is an example view of a tracking target in a spherical coordinate system;

FIG. **4** is a diagram view of a method of an invention embodiment;

FIG. **5**A is a two-dimensional example view of a moving radar passing stationary targets;

FIG. **5**B is a frequency output view of data produced according to FIG. **5**A;

FIG. **5**C is a time series view of magnitude and frequency output of data produced according to FIG. **5**A;

FIG. **6** is an example view of regular sampling and time-warping sampling of a method of an invention embodiment;

FIG. **7** is an example view of varied transform periods of a method of an invention embodiment; and

FIG. **8** is an example view of time-warping of a method of an invention embodiment.

DESCRIPTION OF THE INVENTION EMBODIMENTS

The following description of the invention embodiments of the invention is not intended to limit the invention to these invention embodiments, but rather to enable any person skilled in the art to make and use this invention.

1. System for Doppler-enhanced Radar Tracking

A system **100** for Doppler-enhanced radar tracking includes a transmitter **110**, a horizontal receiver array **120**, and a signal processor **140**, as shown in FIG. **2**. The system **100** may additionally include a vertical receiver array **130** and/or a velocity sensing module **150**.

As discussed in the background section, traditional array-based radar systems are limited: angular resolution depends both on the number of elements in the array and the angle between the array and the target:

$$\theta_{resolution} \approx \frac{\lambda}{Nd\cos\theta}$$

where N is the number of elements in the array and d is the distance separating them.

The system **100** utilizes Doppler frequency shift data in addition to traditional data sources (e.g., relative phase to determine elevation/azimuth angle) to provide enhanced accuracy. Frequency shifts due to the Doppler effect are frequently used by radar systems to provide an estimate of relative velocity between radar and target; however, on its own, Doppler data can only provide information about the rate of change of range

$$\frac{dR}{dt}.$$

This is fine for applications like traffic control, where radar guns are aligned directly with the direction of travel of targets (e.g., the angle between the line segment connecting target and radar gun and the direction of relative velocity between the target and radar gun is close to zero); however, at non-negligible angles there is a significant difference between

$$\frac{dR}{dt}$$

and the actual relative velocity.

While this fact is detrimental for many radar systems, the system **100** takes advantage of this discrepancy in cases where the relative velocity between radar and target is known. In such situations, the composite angle between the radar and the target can be derived. One particular situation involves tracking stationary targets in a moving vehicle with a known velocity. This composite angle can then be used to aid in deriving a tracking solution for the target, thus providing improved angular resolution over traditional systems.

The transmitter **110** functions to transmit a signal that, after reflection by a target, can provide information about the target (e.g., relative location, velocity, etc.). The transmitter **110** preferably transmits a frequency shift keyed (FSK) RADAR signal or a frequency-modified continuous wave (FMCW) RADAR signal, but the transmitter **110** may transmit any signal satisfying these constraints; e.g., an electromagnetic signal (as in radio waves in RADAR, infrared/visible/UV waves in LIDAR), a sound signal (as in SONAR).

The transmitter **110** preferably has a single transmitting element (e.g., a single transmit antenna), but may additionally or alternatively have multiple transmitting elements (e.g., as in a radar array). If the transmitter **110** has multiple elements, these elements may include a single transmitter paired to multiple antennas (e.g., spaced in a particular pattern and/or with antennas coupled to phase/time delays); multiple transmitters, each paired to a single antenna; multiple transmitters paired to multiple antennas, or any other configuration.

The horizontal receiver array **120** functions to receive data resulting from the reflection of the probe signal(s) transmitted by the transmitter **110**. The horizontal receiver array **120** preferably measures phase, magnitude, and frequency information from reflected probe signals, but the horizontal receiver array **120** may additionally or alternatively measure any available characteristics of the reflected probe signals.

From data received from the horizontal receiver array **120**, tracking parameters relating to a tracking target may be calculated. The horizontal receiver array **120** is preferably used to determine azimuth (α), as shown in FIG. **3**A, but parameters used to establish target position may be defined in any coordinate system and base, and the horizontal receiver array **120** may be used to determine any relevant tracking parameters. In the present application, target position is preferably represented in a Cartesian coordinate system with the origin at the radar (e.g., x,y,z represents target position) or a spherical coordinate system with the same origin, wherein position is defined by range (R), azimuth (α), and elevation (θ); alternatively, target position may be described in any manner. Note that elevation (and similarly azimuth) is an example of an angle between a reference vector and a projected target vector; the projected target vector is the vector between the observer (e.g., the radar) and the target, projected into a reference plane (the reference plane containing the reference vector). The system **100** may calculate any such angles.

Note that a reference vector is any vector to which an angle may be referenced (where the angle is between some first vector and the reference vector). A reference vector may be thought of as a vector basis (or a subset of a vector basis) of a vector space that contains the first vector (however, note that the vector bases need not be the same between reference vectors used by different angles). A reference plane can be any plane completely containing a reference vector. In one example, as shown in FIG. **3**B, a first reference vector is a vector along the y axis (and the azimuth angle alpha is referenced to this first reference vector, as is the composite angle beta—though note that these two angles may not necessarily share a reference vector, and that a reference vector for the composite angle beta may be referred to as a "composite reference angle"), and a second reference vector is a vector along the z axis (and the elevation angle theta is referenced to this vector). Likewise, a first reference plane (the plane in which azimuth is measured) is the xy plane, and a second reference plane (the plane in which elevation is measured) is the zy plane. Note also that reference vectors and/or reference planes may be chosen to coincide with RADAR axes as shown in FIG. **3**B (though reference vectors may alternatively be rotated or translated relative to RADAR axes in any manner).

The horizontal receiver array **120** includes a set of receiver elements arranged in a pattern; e.g., along a horizontal axis. The set of receiver elements may include a single receiver paired to multiple antennas (e.g., spaced in a particular pattern and/or with antennas coupled to phase/time delays); multiple receivers, each paired to a single antenna; multiple receivers paired to multiple antennas, or any other configuration.

The horizontal receiver array **120** preferably is used to calculate angles from phase information (as described in FIG. **1**), but may additionally or alternatively be used to calculate angles in any manner (e.g., using horizontal component of Doppler frequency shift).

The vertical receiver array **130** is preferably substantially similar to the horizontal receiver array **120**, except that the vertical receiver array is arranged upon an axis not parallel to the axis of the horizontal receiver array (e.g., a vertical axis). The vertical receiver array **130** is preferably used to calculate elevation, but may additionally or alternatively be used to calculate any tracking parameters.

The signal processor **140** functions to calculate tracking parameters from data collected by the horizontal receiver array **120**, the vertical receiver array **130**, and/or the velocity sensing module **150**. The signal processor **140** preferably includes a microprocessor or microcontroller that calculates tracking parameters according to the method **200**; additionally or alternatively, the signal processor **140** may calculate tracking parameters in any manner. The signal processor **140** may additionally or alternatively be used to communicate with an external computer (e.g., to offload computations, receive additional data, or for any other reason). The signal processor **140** may also control configuration of the components of the system **100** or any calculations or actions performed by the system **100**.

The velocity sensing module **150** functions to determine the velocity of the system **100** (or components of the system **100**, or an object coupled to the system **100**). The velocity sensing module is preferably a communications interface that couples to an inertial measurement unit (IMU), but may additionally or alternatively be any communications interface (e.g., Wi-Fi, Ethernet, ODB-II) or sensor (accelerometer, wheel speed sensor, IMU) capable of determining a speed and/or velocity.

2. Method for Doppler-enhanced Radar Tracking

A method **200** for Doppler-enhanced radar tracking includes transmitting a probe signal S**210**, receiving a reflected probe signal S**220**, and calculating initial tracking parameters from the reflected probe signal S**230**, as shown in FIG. **4**. The method **200** may additionally include refining the initial tracking parameters S**240**.

As discussed in the background section, traditional array-based radar systems are limited: angular resolution depends both on the number of elements in the array and the angle between the array and the target:

$$\theta_{resolution} \approx \frac{\lambda}{Nd\cos\theta}$$

where N is the number of elements in the array and d is the distance separating them.

The method **200** utilizes Doppler frequency shift data in addition to traditional data sources (e.g., relative phase to determine elevation/azimuth angle) to provide enhanced accuracy. Frequency shifts due to the Doppler effect are frequently used by radar systems to provide an estimate of relative velocity between radar and target; however, on its own, Doppler data can only provide information about the rate of change of range

$$\frac{dR}{dt}.$$

This is fine for applications like traffic control, where radar guns are aligned directly with the direction of travel of targets (e.g., the angle between the line segment connecting target and radar gun and the direction of relative velocity between the target and radar gun is close to zero); however, at non-negligible angles there is a significant difference between

$$\frac{dR}{dt}$$

and the actual relative velocity.

While this fact is detrimental for many radar systems, the method **200** takes advantage of this discrepancy in cases where the relative velocity between radar and target is known. In such situations, the composite angle between the radar and the target can be derived. One particular situation involves tracking stationary targets in a moving vehicle with a known velocity. This composite angle can then be used to aid in deriving a tracking solution for the target, thus providing improved angular resolution over traditional systems.

The method **200** is preferably implemented by a system for Doppler-enhanced radar tracking (e.g., the system **100**), but may additionally or alternatively be implemented using any suitable object tracking system capable of receiving Doppler shift information (e.g., SONAR, LIDAR).

S**210** includes transmitting a probe signal. S**210** functions to transmit a signal that, after reflection by a target, can provide information about the target (e.g., relative location, velocity, etc.). S**210** preferably includes transmitting a frequency shift keyed (FSK) RADAR signal or a frequency-modified continuous wave (FMCW) RADAR signal, but S**210** may include transmitting any signal satisfying these constraints; e.g., an electromagnetic signal (as in radio waves in RADAR, infrared/visible/UV waves in LIDAR), a sound signal (as in SONAR).

S**220** includes receiving a reflected probe signal. S**220** functions to receive data resulting from the reflection of the probe signal transmitted in S**210**. S**220** preferably includes measuring phase, magnitude, and frequency information from reflected probe signals, but S**220** may additionally or alternatively include measuring any available characteristics of the reflected probe signals.

S**230** includes calculating initial tracking parameters from the reflected probe signal. S**230** functions to calculate a set of tracking parameters that identify at least a position of the target relative to the radar receiver; additionally or alternatively, tracking parameters may include additional parameters relevant to object tracking (e.g., target velocity, target acceleration). Note that S**230** may include calculating more tracking parameters for a given target than necessary to achieve a position solution; for example, as described later, while only range, azimuth angle, and elevation angle may be necessary to calculate object position, composite angle may also be calculated and used to refine and/or check azimuth/elevation angle calculations.

Further, while S**230** primarily includes calculating tracking parameters from the reflected probe signal, S**230** may additionally or alternatively calculate or otherwise receive parameters relevant to object tracking (e.g., radar egomotion velocity) that are not calculated using the probe signal.

Parameters used to establish target position may be defined in any coordinate system and base. In the present application, target position is preferably represented in a Cartesian coordinate system with the origin at the radar (e.g., x,y,z represents target position) or a spherical coordinate system with the same origin, wherein position is defined by range (R), azimuth (α), and elevation (θ); alternatively, target position may be described in any manner. Note that elevation (and similarly azimuth) is an example of an angle between a reference vector and a projected target vector; the projected target vector is the vector between the observer (e.g., the radar) and the target, projected into a reference plane (the reference plane containing the reference vector). The method **200** may include calculating any such angles.

While, as previously mentioned, any parameters relevant to object tracking may be calculated in S**230**, some additional parameters that may be calculated include target range rate

$$(\frac{dR}{dt},$$

typically calculated from Doppler data), relative target velocity (the velocity of the target with respect to the radar receiver), radar egomotion velocity (referred to in this application as egovelocity, the velocity of the radar receiver relative to a stationary position). These may be related; for example, range rate is equivalent to relative target velocity multiplied by the cosine of the looking angle between the radar and the target.

S**230** may additionally or alternatively include calculating composite angle (β, the angle between the target and the radar: β=arccos [cos $\alpha\times$cos θ], see also FIG. **3**A). While composite angle may be derived from elevation and azimuth (or vice versa), it may also be calculated from Doppler data. If, for example, elevation and azimuth are calculated from a first data source (e.g., phase differences between receivers in a receiver array) and composite angle is calculated from a second data source (e.g., Doppler frequency shift and relative velocity), composite angle can be used alongside elevation and azimuth to produce a more accurate solution.

S**230** may include calculating tracking parameters from any suitable data source. For example, operating on a radar system with a horizontal receiver array, azimuth may be calculated based on phase differences between the reflected probe signal seen by each receiver in the array. Likewise, elevation may be calculated in a similar manner by a vertical receiver array (and/or elevation and azimuth may be calculated in similar manners by a two-dimensional receiver array). Range, for example, may be calculated based on travel time of a probe signal. Range rate, for example, may be calculated instantaneously (e.g., using Doppler frequency shift data) or over time (e.g., by measuring change in range over time). Composite angle, as previously discussed, may be derived from elevation/azimuth or calculated explicitly from Doppler data:

$$f_D \approx Kv\cos\beta;\ K = 2\frac{f_0}{c}.$$

S**230** may additionally include calculating relative target velocity in any manner. For example, S**230** may include determining that a target is stationary and calculating relative target velocity based on egovelocity (i.e., in this case, relative target velocity is egovelocity). A target may be determined as stationary in any manner; for example, by identifying the target visually as a stationary target (e.g., a stop sign may be identified by its appearance), by identifying the target by its radar cross-section as a stationary target (e.g., a stop sign or a road may be identified by shape or other features), by comparing Doppler data to other (e.g., phase) data (e.g., if the composite angle provided by Doppler data is substantially different from the composite angle derived from elevation and azimuth, that may be a moving target), by the size of the target, or in any other manner. Likewise, egovelocity may be determined in any manner (e.g., a GPS receiver or IMU coupled to the position of the radar receiver, external tracking systems, etc.). As another example, S**230** may include receiving relative target velocity information based on external data; e.g., an estimate from a visual tracking system coupled to the position of the radar receiver. Relative target velocity information may even be provided by an external tracking system or the target itself (e.g., transmissions of IMU data from a target vehicle).

In an example implementation of the method **200**, S**230** includes calculating elevation (though this angle may be any angle in a plane perpendicular to a receiver array; e.g., azimuth) using phase or time difference information and calculating composite angle using Doppler frequency shift data and velocity data. This example implementation is preferably used with a one-dimensional radar array (which, using traditional techniques, is capable of determining only elevation and not azimuth), but may additionally or alternatively be used with any radar system. In this example implementation, the composite angle may be used, along with the elevation and range, to produce a tracking solution. Note that this example implementation both expands the dimensionality of the radar array (producing three-dimensional data instead of two-dimensional data from the one-dimensional array), and also provides for increased accuracy over a traditional two-dimensional radar array (because the angular resolution of the Doppler-generated composite angle is often higher than the angular resolution of elevation and azimuth generated by traditional solutions).

In a second example implementation of the method **200**, S**230** includes calculating elevation and azimuth (though this angle may be any two perpendicular angles in a plane perpendicular to a receiver array) using phase or time difference information and calculating composite angle using Doppler frequency shift data and velocity data. This example implementation is preferably used with a two-dimensional radar array (which, using traditional techniques, is capable of determining both elevation and azimuth), but may additionally or alternatively be used with any radar system. In this example implementation, the composite angle may be used, along with the elevation, azimuth and range, to produce a tracking solution. In this example, the composite angle may be used as a constraint or filter to improve the accuracy of elevation and azimuth estimates, thus greatly improving the accuracy of the data produced.

While simply using Doppler-derived angles already provides substantial improvement to traditional techniques, S**230** may include multiple techniques for providing additional improvement.

For example, the relative velocity of radar targets changes (in many applications) substantially slower than sample rate of Doppler shift; accordingly, velocity data may be averaged or otherwise smoothed to reduce noise and improve accuracy. Given a Doppler shift sample k and consecutive sample k+1:

$$f_{Dk}=Kv_k \cos \beta_k; f_{Dk+1}=Kv_{k+1} \cos \beta_{k+1}$$

requirements on velocity can be relaxed ($v_k \approx v_{k+1}$), leading to:

$$\frac{f_{Dk}}{f_{Dk+1}} = \frac{\cos \beta_k}{\cos \beta_{k+1}}$$

To determine Doppler frequency shift, S**230** may include converting reflected signal data to the frequency domain using a Fast Fourier Transform (or any other technique to convert time domain signals to frequency domain for analysis). S**230** may also improve system performance by using a Sliding Fast Fourier transform (SFFT) or similar techniques such as the Sliding Discrete Fourier Transform (SDFT) and Short-time Fourier Transform (STFT). These techniques allow Fourier transforms for successive samples in a sample stream to be computed with substantially lower computational overhead, improving performance.

For example, a moving radar passes two stationary targets (target a and target b) while moving at a constant velocity v, as shown in FIG. **5**A. At each time sample, the radar has moved, and thus the composite angles between the radar and the targets have changed (e.g., βb**4** corresponds to the composite angle formed between the radar and target b at end of time period T**4**). Taking the Fourier transform with respect to time provides the Doppler frequency shift data as shown in FIG. **5**B and FIG. **5**C. Note that as the composite angles go from their largest to smallest, a few effects happen. Given the aforementioned constant velocity:

$$\beta_a(y) = \arctan\frac{x_a}{y};\ \beta_b(y) = \arctan\frac{x_b}{y}$$

$$f_{Da}(y) = Kv \cos \arctan\frac{x_a}{y} = \frac{Kv}{\sqrt{1+\frac{x_a^2}{y^2}}};\ f_{Db}(y) = \frac{Kv}{\sqrt{1+\frac{x_b^2}{y^2}}}$$

$$\Delta f_D = Kv\left(\frac{1}{\sqrt{1+\frac{x_a^2}{y^2}}} - \frac{1}{\sqrt{1+\frac{x_b^2}{y^2}}}\right)$$

$$\beta = \arccos\frac{f_D}{Kv}$$

Thus, the first effect is simply that the rate of change of Doppler frequency shift with respect to β increases as β increases (increasing angular resolution as $\beta \rightarrow \beta_{max}$). The second effect is that the difference in composite angle between two closely spaced targets increases as from o as β:0→45° and then decreases thereafter (to zero at β=90°). This suggests that even as angular resolution increases, it may be more difficult to distinguish two targets at large angles relying solely on β. That being said, the effect of increase in resolution outpaces the decrease in angle until β≈55° (angle of maximum angular separation between two closely spaced targets), and Δf_D does not again approach the value at has at 20 degrees (a typical angle) until 83 degrees (a very large angle) suggesting that the majority of this impact may apply in angular ranges not covered by radar.

The third effect follows from exposing time dependence of the composite angle. As the radar approaches the target,

$$\frac{d\beta}{dt}$$

increases; resultantly, the sampling time for a given angular interval decreases (alternatively stated, in a given time period, the angle changes more), causing smearing in the Fourier transform required to calculate Doppler shift and reducing the ability to distinguish targets.

While **S230** may include calculating composite angle directly from the Fourier transform of reflected probe signal data (e.g., by taking the center frequency of the frequency bucket with the highest magnitude as the Doppler frequency shift), **S230** may additionally or alternatively include producing (for each time period of a set) a set of angle-adjusted frequency outputs **S232**. **S232** preferably includes generating one or modified outputs from the reflected probe signal based on a predicted composite angle (B, distinct from actual composite angle β). In one invention embodiment, **S232** includes generating (for a set of angle ranges from $\{B_{min}, B_{min}+\Delta\}$ to $\{B_{max}-\Delta, B_{max}\}$) a set of Fourier transformed outputs for each angle range in the set. Take, for example, a signal of $\cos[2\pi f_{Dmax} t \cos\beta]$. Instead of taking the Fourier transform with respect to t (the traditional technique), **S232** may include taking the Fourier transform with respect to $\tau = t\cos B$ for each angle range (e.g., by taking the transform with respect to $\tau = t\cos B$ for the center angles of each range), ideally generating an output frequency of

$$2\pi f_{Dmax}\frac{\cos\beta}{\cos B}$$

for a target at angle β.

S232 preferably functions to provide a more consistent and/or more easily implemented method of determining Doppler shift for a given target than traditional implementations; by producing a set of Fourier transformed outputs (each corresponding to a different angle interval), the member of the set with the closest frequency output to f_{Dmax} (the Doppler shift for an angle of zero) can be chosen, thus locating the composite angle within a pre-specified interval. Alternatively, **S232** may be thought of as identifying angle ranges in which targets exist (e.g., angle ranges in which the frequency magnitude around f_{Dmax} is higher than a threshold).

Note that unless the angle ranges are very small at larger angles (requiring more Fourier transforms to be performed for a single time interval), there will likely still be some change in cos β during the sampling period (causing smearing and reduced accuracy).

To address this issue, **S232** may additionally or alternatively include pre-warping reflected signal data while performing the Fourier transform. In an implementation including pre-warping, **S232** preferably functions to effectively warp reflected signal data with respect to changing angles by selectively sampling reflected signal data as input for the Fourier transform.

This may be illustrated as follows. Assume that a radar receiver takes samples at every interval $\{t_0, t_1, \ldots\}$. Without pre-warping, **S232** may include performing discrete Fourier transforms for $\{B_0, B_1 \ldots\}$ with respect to $\tau = t\cos B$ across a subset of these time intervals (frequency resolution is determined by time and not directly by sample rate, so using more samples than necessary to resolve a given Doppler frequency takes more computational time and provides little benefit); say, for example, $\{t_0, t_{10}, t_{20}, t_{30}, t_{40}, t_{50}\}$. At larger target angles, as previously mentioned, target angles may change noticeably during this time period, causing smearing in the output.

To pre-warp, **S232** includes selecting non-uniformly spaced samples in time to reflect the change in angle across an angle interval. For example, to pre-warp the Fourier transform for B_1, **S232** may include selecting samples based on the assumption that over the angle range from $B_1-\Delta$ to $B_1+\Delta$, the composite angle changes linearly with time over the sampling period. The signal can thus be modeled as:

$$\cos\left[2\pi f_{Dmax} t \cos\left[\beta + \Delta\left(\frac{2t}{T} - 1\right)\right]\right] = \cos$$

$$\left[2\pi f_{Dmax} t \cos[\beta]\left(\cos\left[\Delta\left(\frac{2t}{T} - 1\right)\right] + \tan[\beta]\sin\left[\Delta\left(\frac{2t}{T} - 1\right)\right]\right)\right],\ t \to \{0, T\}$$

$$\cos\left[2\pi f_{Dmax} \tau \frac{\cos\beta}{\cos B}\left(\cos\left[\Delta\left(\frac{2\tau}{T\cos B} - 1\right)\right] + \tan[\beta]\sin\left[\Delta\left(\frac{2\tau}{T\cos B} - 1\right)\right]\right)\right],$$
$$\tau \to \{0, T\cos B\}$$

To account for this additional factor on t, the sampling periods in t may be stretched or shrunk. For example, at t=0, t is multiplied by $(\cos[-\Delta]+\tan[\beta]\sin[-\Delta])$. Assuming β=45°, Δ=10° (a large delta is chosen for illustration) this factor is equivalent to 0.81. The corresponding factor at t=T is 1.16. Accordingly, to adjust for this shift, the sampling periods (or sampling frequency) for the Fourier transform may be scaled appropriately, e.g., sampling at $\{t_0, t_{12}, t_{23}, t_{33}, t_{42}, t_{50}\}$, as shown in FIG. **6**.

The transform period for **S232** may be uniform in time across B, (e.g., for B_1, $T=T_1$, $T_\tau = T_1\cos B_1$ while for B_2, $T=T_1$, $T_\tau = T_1\cos B_2$), however, this results in decreased frequency resolution for larger B relative to that of smaller B (i.e., $T_1\cos B_2 < T_1\cos B_1$). Thus, **S232** may additionally or alternatively include modifying transform period based on B to allow for uniform frequency resolution (or alternatively, any modified frequency resolution set), as shown in FIG. **7**.

For example, assume that constant frequency resolution is desired at all B. In this case, the sampling period for each B (in t) should be

$$T = T_1\frac{\cos B_{min}}{\cos B}$$

where the desired frequency resolution at

$$B = B_{min} \text{ is } \frac{1}{T_1}\ \left(\text{e.g., } T_2 = T_1\frac{\cos B_1}{\cos B_2},\ T_3 = T_1\frac{\cos B_1}{\cos B_3}\right).$$

Note that while the example as shown in FIG. **7** utilizes both non-uniform sampling (i.e., time-warping) and varied transform periods, **S230** may alternatively include varying transform periods without performing time-warping.

The examples so far have relied on opportunistically selecting existing samples from a sample stream; however, **S230** may additionally or alternatively include resampling reflected probe signal data **S231**. **S231** preferably includes resampling reflected probe signal data per angle B based on a desired set of sampling times. For example, in the example shown in FIG. **6**, **S232** sampled at $\{t_0, t_{12}, t_{23}, t_{33}, t_{42}, t_{50}\}$, but these sample numbers were not based on exact scaling factors (rather, the closest available sample to a scaling factor was selected). Using one method of calculating time samples (subdividing the time window into segments scaled by the center angle of those segments, assuming composite angle changes linearly with time), as shown in FIG. **8**, the following set may be desired for sampling $\{t_0, t_{11.66}, t_{22.27}, t_{32.12}, t_{41.39}, t_{50}\}$. Since these indices do not correspond to samples, S**231** preferably includes resampling the reflected probe signal data to generate these values. S**231** may include resampling the reflected probe signal data in any manner; e.g., via linear interpolation ($t_{11.66}=t_{11}+0.66(t_{12}-t_{11})$). S**231** may include determining sampling periods for resampling in any manner.

In a first example implementation, S**230** includes dividing an angular space (e.g., $\{B_{min}, B_{max}\}$) into uniform ranges (e.g., {15°±50, 25°±50, 35°±50, 45°±5°} for an angle range from 10 to 50 degrees). Alternatively, S**230** may include selecting composite angles or angular ranges in any manner. Note that the set of angular ranges may be continuous and non-overlapping (e.g., 15°±5°, 25°±5°), but may additionally or alternatively be discontinuous (e.g., 15°±2°, 25°±2°) and/or overlapping (e.g., 15°±10°, 25°±5°). Further note that while angular ranges may be uniform, they may additionally or alternatively be non-uniform.

After determining the set of angles (or angle ranges) for which computation (in S**232**) is to be performed, S**230** preferably includes determining the overall transform period for each angle. S**230** may include determining this in any manner (e.g., by scaling the time periods such that they are equal in T as previously described). Then, S**230** preferably includes determining how sampling should be performed for each of the angles (e.g., how the FFT block is divided). As previously described, one technique for doing this involves selecting a base sampling period (e.g., every ten samples, or every 10 ms) and then warping the sampling periods to account for linear change in angle over that time. For example, if the base sampling period is 10 ms for an angle range $B_1\pm\Delta$ centered at B_1 and an overall transform period of 50 ms, the first sampling period may be T_{B1a}, where

$$T_{B1a} = 2t_{B1a} = 10\text{ms} \times \frac{\cos B_{1a}}{\cos B_1}; B_{1a} = B_1 - \Delta + \frac{2\Delta t_{B1a}}{50\text{ms}},$$

as shown in FIG. **8**. Likewise, the second period may be chosen so

$$T_{B1b} = 2(t_{B1b} - 2t_{B1a}) = 10\text{ms} \times \frac{\cos B_{1b}}{\cos B_1}; B_{1b} = B_1 - \Delta + \frac{2\Delta t_{B1b}}{50\text{ms}},$$

so on and so forth.

After generation of these periods, resampling (if desired) may be performed in S**231** (alternatively, existing samples may be selected in any manner; e.g., to achieve time-warping) and then Fourier transforms may be performed in S**232** for each angle.

In a variation of an invention embodiment, S**230** includes performing multiple Fourier passes; for example, performing transforms for angle ranges of 25±10° and 35±10°, detecting that one or more targets exists in the 35±10° range, and then performing transforms for 30±5°, 35±5°, and 40±5° ranges in a second pass.

S**240** includes refining the initial tracking parameters. S**240** functions to generate a more accurate tracking solution than that initially calculated by S**230**. In a first example implementation, S**240** includes running a Kalman filter on Cartesian coordinates of a target generated from elevation angle or azimuth angle (determined from phase information), range, and composite angle (determined from Doppler shift), constrained by error bounds of the composite angle. In a second example implementation, S**240** includes running a Kalman filter on Cartesian coordinates of a target generated from elevation angle and azimuth angle (determined from phase information), range, and composite angle (determined from Doppler shift), constrained by error bounds of the composite angle.

S**240** may additionally or alternatively include filtering, refining, and/or constraining tracking parameters in any manner.

The methods of the preferred embodiment and variations thereof can be embodied and/or implemented at least in part as a machine configured to receive a computer-readable medium storing computer-readable instruction. The instructions are preferably executed by computer-executable components preferably integrated with a system for Doppler-enhanced radar tracking. The computer-readable medium can be stored on any suitable computer-readable media such as RAMs, ROMs, flash memory, EEPROMs, optical devices (CD or DVD), hard drives, floppy drives, or any suitable device. The computer-executable component is preferably a general or application specific processor, but any suitable dedicated hardware or hardware/firmware combination device can alternatively or additionally execute the instructions.

As a person skilled in the art will recognize from the previous detailed description and from the figures and claims, modifications and changes can be made to the preferred embodiments of the invention without departing from the scope of this invention defined in the following claims.

We claim:

1. A method for Doppler-enhanced radar tracking comprises:

receiving egovelocity data;

transmitting a probe signal;

receiving a reflected probe signal at a radar array in response to reflection of the probe signal by a tracking target, wherein the tracking target and radar array are spatially related by a target vector; wherein the radar array comprises a first plurality of radar elements positioned along a first radar axis;

calculating a target range from the reflected probe signal;

calculating a first target angle between a first reference vector and a first projected target vector from the reflected probe signal; wherein the first projected target vector is the target vector projected into a first reference plane, the first reference plane containing both of the first radar axis and the first reference vector; wherein calculating the first target angle comprises calculating the first target angle from phase differences in the reflected probe signal as received by the first plurality of radar elements;

calculating a target composite angle from the reflected probe signal; wherein the target composite angle is an angle between the target vector and a composite reference vector; wherein calculating the target composite angle comprises:

calculating Doppler frequency shift data from the probe signal and reflected probe signal, comprising generating a set of predicted target composite angles and generating a set of Fourier transformed outputs for each of the set of predicted target composite angles; and

calculating the target composite angle from the egovelocity data and the Doppler frequency shift data; and calculating a three-dimensional position of the tracking target relative to the radar array from the target range, first target angle, and target composite angle.

2. The method of claim **1**, wherein calculating the first target angle comprises calculating one of elevation and azimuth.

3. The method of claim **1**, further comprising determining that the tracking target is stationary and calculating relative target velocity based on egovelocity.

4. The method of claim **1**, wherein generating the set of Fourier transformed outputs for each of the set of predicted target composite angles comprises performing Fourier transforms with respect to a set of tau variables, wherein each tau variable is equal to a time variable multiplied by a cosine of one of the set of predicted target composite angles.

5. The method of claim **4**, wherein generating the set of Fourier transformed outputs for each of the set of predicted target composite angles comprises performing Fourier transforms for each of the set of predicted target composite angles over periods of time determined by each of the set of predicted target composite angles.

6. The method of claim **5**, wherein performing Fourier transforms for each of the set of predicted target composite angles comprises performing Fourier transforms for each of the set of predicted target composite angles over periods of time set by dividing a base time period by cosines of each of the set of predicted target composite angles.

7. The method of claim **5**, wherein performing Fourier transforms for each of the set of predicted target composite angles comprises pre-warping reflected probe signal data to account for change in the target composite angle over time.

8. The method of claim **7**, wherein pre-warping reflected probe signal data comprises selecting existing reflected probe signal data samples such that sampling frequencies are non-uniform.

9. The method of claim **8**, wherein selecting existing reflected probe signal data samples comprises selecting existing reflected probe signal data samples assuming a linear change in the target composite angle over time.

10. The method of claim **7**, wherein pre-warping reflected probe signal data comprises resampling reflected probe signal data samples with non-uniform sampling frequencies.

11. The method of claim **10**, wherein resampling reflected probe signal data samples comprises resampling reflected probe signal data samples assuming a linear change in the target composite angle over time.

12. A method for Doppler-enhanced radar tracking comprises:

receiving egovelocity data;

transmitting a probe signal;

receiving a reflected probe signal at a radar array in response to reflection of the probe signal by a tracking target, wherein the tracking target and radar array are spatially related by a target vector; wherein the radar array comprises a first plurality of radar elements positioned along a first radar axis, and a second plurality of radar elements positioned along a second radar axis, the second radar axis not parallel to the first radar axis;

calculating a target range from the reflected probe signal;

calculating a first target angle between a first reference vector and a first projected target vector from the reflected probe signal; wherein the first projected target vector is the target vector projected into a first reference plane, the first reference plane containing both of the first radar axis and the first reference vector; wherein calculating the first target angle comprises calculating the first target angle from phase differences in the reflected probe signal as received by the first plurality of radar elements;

calculating a second target angle between a second reference vector and a second projected target vector from the reflected probe signal; wherein the second projected target vector is the target vector projected into a second reference plane, the second reference plane containing both of the second radar axis and the second reference vector; wherein calculating the second target angle comprises calculating the second target angle from phase differences in the reflected probe signal as received by the second plurality of radar elements;

calculating a target composite angle from the reflected probe signal; wherein the target composite angle is an angle between the target vector and a composite reference vector; wherein calculating the target composite angle comprises:

calculating Doppler frequency shift data from the probe signal and reflected probe signal, comprising generating a set of predicted target composite angles and generating a set of Fourier transformed outputs for each of the set of predicted target composite angles; and

calculating the target composite angle from the egovelocity data and the Doppler frequency shift data; and

calculating a three-dimensional position of the tracking target relative to the radar array from the target range, first target angle, second target angle, and target composite angle.

13. The method of claim **12**, wherein calculating the first target angle comprises calculating elevation and calculating the second target angle comprises calculating azimuth.

14. The method of claim **12**, further comprising determining that the tracking target is stationary and calculating relative target velocity based on egovelocity.

15. The method of claim **12**, wherein generating the set of Fourier transformed outputs for each of the set of predicted target composite angles comprises performing Fourier transforms with respect to a set of tau variables, wherein each tau variable is equal to a time variable multiplied by a cosine of one of the set of predicted target composite angles.

16. The method of claim **15**, wherein generating the set of Fourier transformed outputs for each of the set of predicted target composite angles comprises performing Fourier transforms for each of the set of predicted target composite angles over periods of time determined by each of the set of predicted target composite angles.

17. The method of claim **16**, wherein performing Fourier transforms for each of the set of predicted target composite angles comprises performing Fourier transforms for each of the set of predicted target composite angles over periods of time set by dividing a base time period by cosines of each of the set of predicted target composite angles.

18. The method of claim **16**, wherein performing Fourier transforms for each of the set of predicted target composite angles comprises pre-warping reflected probe signal data to account for change in the target composite angle over time.

19. The method of claim **18**, wherein pre-warping reflected probe signal data comprises selecting existing reflected probe signal data samples such that sampling frequencies are non-uniform.

20. The method of claim **19**, wherein selecting existing reflected probe signal data samples comprises selecting existing reflected probe signal data samples assuming a linear change in the target composite angle over time.

21. The method of claim **18**, wherein pre-warping reflected probe signal data comprises resampling reflected probe signal data samples with non-uniform sampling frequencies.

22. The method of claim **21**, wherein resampling reflected probe signal data samples comprises resampling reflected probe signal data samples assuming a linear change in the target composite angle over time.

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